Ground-based Validation of the EOS Multi-angle Imaging SpectroRadiometer (MISR) Aerosol Retrieval Algorithms and Science Data Products

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Abstract -- A plan for the ground-based validation of MISR aerosol retrieval is outlined. Activities occur in two phases: (1) pre-launch, work is focused on technique development and MISR algorithm validation using conventional ground-based methods and a MISR simulator (AirMISR) operating from the ER-2 aircraft to simulate MISR on-orbit observations. (2) Post-launch, [he validation program relies on ground campaigns, underflights with the MISR simulator and the use 01 local measurements of' aerosol loading and properties anti irradiance measurements derived from the AERONET and ISIS networks.

INI'RODLJCI'1ON

We outline a ground-based program for validation of aerosol recovery algorithms and post-launch science data products from the Multi-angle Imaging SpectroRadiometer (MISR). The ground optical measurements program employs convent ional instrumenta tion for measu e ment of diffuse sky spectral radiances and irradiances and direct spectral solar radiances, and a new sphere scanning radiometer (downwelling and upwelling spectral radiances) for estimation of the surface bidirectional reflectance factor (BRF). Interpretation of the atmospheric measurements in terms of aerosol microphysical properties is carried out using inversion methods and algorithms available from the literature and developed over the past 20 years or so by numerous investigators. Here an attempt is made to combine various methods to secure estimates of all of the aerosol physical properties important in the MISR retrieval process independently of assumptions made in the MISR retrievals. An aircraft simulator (AirMISR) is under development for usc on the ER-2 aircraft platform to provide near-TOA multi-angle radiance measurements at MISR wavelengths of ground targets over the entire range of instrument view angles, AirMISR will replace the **Advanced** Solid State Array Spectrometer (ASAS) which operated from the lower altitude C- 130 aircraft platform, and which has heretofore acted as the MISR simulator. The simulator data will be used to provide estimates of the retrieved optical depths and aerosol properties according to the MISR retrieval strategy for comparison with results of ground measurements. Radiative closure is checked by comparison of measured sky radiances with those calculated for the retrieved aerosol model using a radiative transfer code.

wc provide herein descriptions of MISR and the MISR experiment, the MISR aerosol recovery strategy, the field instrumentat ion, and the field-based aerosol recovery algorithms,

DEFINITION OF TERMS

The process of validation implies here intercomparison of aerosol properties derived from MISR-simulator or MISR measurements using MISR procedures, with aerosol properties derived from ground-based measurements and conventional interpretation or inversion methods. Implied in all present validation studies is a comprehensive analysis of experimental uncertainties. This suggests a second possibly independent definition of validation, also sought here, as the Complete understanding of the uncertainties (both systematic and random error) in each experimental path.

Validation field experiments consist of overflights of a chosen target by the MISR simulator duplicating the overpass of MISR on orbit in azimuth, direction, and local time of overpass. Simultaneously, field measurements of atmospheric and surface reflectance properties are carried out in the target area. Where possible, comparisons of radiatively retrieved aerosol properties from the ground will be compared with direct aerosol measurements, either ground-based or from aircraft.

MISR EXPERIMENT OVERVIEW

MISR is scheduled for launch on the EOS AM-1 platform in mid-1998. MISR will provide radiometrically calibrated, stable radiance measurements coregistered at nine view angles (±70.5°, ±60°, ±45.6°, ±26.1°, t)") and four wavelengths (443, S55, 670, and 865 nm) globally over a 360 km swath of the Earth's surface on each pass. The fundamental cross-track pixel size at the surface is 275 m for all off-nadir pixels and 250 m in the nadir camera. From these 36 multi-angle and multispectral observations, estimates of atmospheric aerosol abundance and composition, surface bidirectional reflectance properties, cloud top heights and albedo of cloud layers, surface and cloud albedo together for mixed scenes, and the surface albedo alone in cloud-free areas will be obtained. Such data will be employed for improved determinations of the effects of aerosol burden on atmospheric heating and cooling via constraint of the global aerosol budget, for identification of sources and sinks of aerosols, for surface and atmospheric radiation balance through measurement of the surface and TOA albedos, and for improved classification of surfaces and surface architecture via specificat ion of the spectral BRF.

From the perspective of timing of ground-based validation campaigns or MISR simulator underflights, at northern mid-i atitudes, the expected MISR on orbit overpass time is about 10:15 A.M local time at a heading of about 190°.

MISR AEROSOL RETRIEVAL STRATEGY

The principal MISR aerosol science data product is the column aerosol optical depth, reported at a wavelength of ss5 nm, together with aerosol type. and with spatial sampling of 17.6 km globally. These retrievals are carried out for all cloud-flee areas. The MISR-based retrieval of aerosol amount and aerosol type arc carried out by minimizing residuals between [he observed radiances on orbit and radiances precalculated from a radiative transfer model.

A collection of mixtures globally representative dry aerosol components and characteristic sizes together with an adsorbed water component driven by atmospheric RH, is assumed in an aerosol climatology data base used in the aerosol retrieval. The generic pure particle types assumed in the aerosol climatology are: (1) sulfate/nitrate, **(2)** mineral dust, (3) sea salt, **(4)** urban soot, (5) biomass burning particulates, (6) near surface fog, and (7) thin cirrus. For each of these, the particle size distribution is taken as log-normal except 101'10: and mineral dust, which arc assumed to follow power laws. A characteristic radius, size limits, real and imaginary refractive indices (sometimes variable with wavelength), and particle shape are specified. All particles are assumed spherical except for dust (prolate/oblate spheroids) or cirrus (fractal facet geometry).

Three retrieval pathways arc specified for surface reflectance to separate surface-reflected and path radiance components: (1) dark ocean or lake waters, (2) dense dark vegetation (DDV), and (3) heterogeneous land. Reflectance characteristics of surface types (1) and (2) arc specified from selected standard DDV BRF models. The retrieval path for type (3) utilizes spatial variations in the surface reflectance (hence heterogeneous) to develop an Empirical Orthogonal Function (EOF) representation ol'the angular variation of the scene reflectance, which is employed to separate surface-reflected and path radiance components. Subsequently, for all pathways the procedure is to match observed radiances with calculated radiances for different models in the climatology tables using the path radiance (zero surface reflectance) alone. These procedures are explained in detail in [1].

ALGORITHM AND PRODUCT VAL.11)A"1'1ON

MISR validation activities arc divided into two phases: (1) pre-launch, focused on accumulation o! instrumentation, development of methodology, and field exercises aimed at algorithm validation; (2) post-launch, focused on validation of the on-orbit instrument calibration and upon product validation using field experiments coordinated with overflights together with observations from automated networks of sunphotometers including AERONET [2] and radiation instruments of the 1S1S network [3].

Field Instruments and MISR Aircraft Simulator AirMISR

The principal field instruments used for retrieval of aerosol optical depth and microphysical properties and for determination of surface BRF arc described:

CIMEL Sky and Sun Photometer: The CIMEL CE 318-3 is an automated instrument capable of' long term monitoring of both direct solar irradiance and diffuse sky irradiance in the solar almucantar and principal plane, and can operate over extended numbers of days unattended. It is the principal instrument of the so-called AERONET aerosol monitoring network [2] and will therefore play an important role in post-launch MISR as well as MODIS product validation. Observations at resolution of 10 nm arc made by filters at wavelengths of 300, 340, 380, 440, 670, 870, 940, and 1020 nm. The data form principal input to software [4] for columnar aerosol features. A data transmission system through geostationary satellites feeds field information to computers at Goddard Spaceflight Center.

Reagan Sunphotometer: The so-called Reagan sunphotometers (manufactured by J. A. Reagan, University of Arizona) automatically track the sun and record direct solar irradiance. These data can be used for determination of atmospheric total spectral optical depth and for the separation of it into molecular, ozone, water vapor and aerosol optical depth components based on the so-called Langley method. The ten filter channels (7-17 nm width) recorded are near 380, 400, 440, 520, 610, 670, 780, 870, 940 and 1030 nm.

MultiFilter Rotating Shadowband Radiometer: The Multifilter Rotating Shadowband Radiometer (MFRSR), [5], provides automated, unattended recording and separation of total-horizontal, direct-normal, and diffuse-horizontal irradiances. The instrument forms one component of the ISIS radiation network [3]. Six narrowband filter *channels* (each 10 nm) are located at 415, 500, 610, 665, and 862 nm, and a broadband unfiltered channel covering about 300- 1000" nm. These data provide aerosol optical depths, water vapor column abundance, plus direct measurement of surface spectral irradiance for- comparison with MISR-calculated quantities, The data are used with theoretical models (*e. g.*, [6], [7], [8]) for estimation of a regional Lambertian surface reflectance and bulk aerosol complex index of ret'[-ac[ion and also to retrieve aerosol optical depth.

Portable Apparatus for Rapid Acquisition of Bi-directional Observations of the Land and Atmosphere (PARABOLA III): This sphere-scanning radiometer has a long previous history in a different mechanical configuration as PARABOLA I [9]. PARABOLA III measures the complete distribution of radiance at a site from both sky and ground hemispheres in 5° fickls-of-view. These data arc used in the defining equation for boundary energy conservation [o estimate the bidirectional reflectance factor (BRF, see [10]). PARABOLA III has bands near 443, 5S1,

650, 861, 948, 400-700 (l'AR), and 1655 nm. In addition to BRF, PARABOLA III will provide high dynamic range radiance measurements in all sky azimuths 5° apart, including zenith to horizon data. These latter measurements provide independent data sets not included in the inverse problems fo r recover y of phase function and size distribution, and are therefore useful in aerosol closure experiments.

ASD/GER Spectrometers: Two spectrometers ar e employed in field operation. The purpose of these instruments is to place the sparse aerosol optical depth and the surface reflectance determinations by MISR in context with data of higher spectral resolution extending over a broader spectral range. Both instruments cover the approximate spectral range from 350-2700 nm with a resolution of' - I 0 nrn and a spectral sampling interval of about 2 nm. The ASD instrument is devoted to rapid measurement of S111-face hemispherical directional reflectance while the GER focuses on recovery of high resolution optical depth of the atmosphere using the Langley method (described below).

AirMISR: AirMISR has been fashioned from a spare MISR camera and mounted on a gimbal to rotate on an axis perpendicular 10 the direction of aircraft motion. Images simulating MISR viewing arc built up for each MISR view angle and wavelength line by line in pushbroom fashion through forward motion of the aircraft. The instrument resides in the nose of the ER-2. At 20 km altitude above the surface, the IFOV of the AirMISR camera of 0.36 mrad provides a ground footprint ranging from 7-22 m along track. The full image size can vary depending on view angle and the programmed time line of' dark current observation, slew, and dwell for image acquisition. For example one extreme acquisition time line (14.96 minutes total elapsed time) generates images ranging from about 11 km on a side at nadir to 25.5 km (along track) x 32.9 km (across track) at the extreme view angles 01 ±70°. The resulting flight lines can be quite lengthy to get the complete angular range, for example in the above, beginning and ending 90.5 km to either side of the target point.

Calibration and Intercomparison of Instruments

Field in.slrwnetlt.s: Because of inherent changes in instrument behavior over time and also because of the small disparities in wavelength between channels of all field instruments already described, these instruments are regularly calibrated and intercompared. The Langley method [11] for determination of instrument V_0 is utilized and other approximate transformation formulas between responses are developed. Calibrations arc carried out at high altitude mountain sites by observing the sun (to experience maximum expected dynamic range) under stable clear sky conditions, 1[is expected that the inherent problem of atmospheric variability with air mass will always be present, but minimized for such sites. In addition the spectral response functions of channels on all instruments are determined in the laboratory using a monochromator with slit width set for 1-2 nm. The calibration of water vapor channels is always determined relative to other channels in the laboratory. Histories of instrument calibration arc kept to track performance changes with time.

Vicarious Calibration of AirMISR and MISR: Vicarious calibration of instruments in-flight is synonymous with use of the so-called reflectance-based method [12]. The calibration of MISR and evaluation of possible instrument drift over time is crucial to the long-term success of detecting secular changes in aerosol and surface characteristics of the F.arth-atmosphere system. 'I'he vicarious calibration pathway is independent of preflight or on-board calibration modes. The vicarious method employs a radiative transfer code (RTC) to predict top-of-atmosphere radiance above a natural target surface. The surface reflectance and the atmospheric optical depth plus an aerosol model anti water vapor abundance are used to constrain the code. The aerosol model itself is constrained by ground-based or, where possible, by direct sampling of aerosol properties. The R1'~-calculated radiance is compared to that predicted at the sensor for the target area given a laboratory or on-board estimate of the calibration. It is expected that dry lake beds in remote desert environments at moderate altitude (-S()()() feet) will be employed to minimize atmospheric interference. An example site is Lunar Lake, NV.

Principal Algorithms

Primary elements of the MISR aerosol validation activity arc: (I) verification of the aerosol optical depths and types retrieved by this novel nlLllti-angle method, (2) establishing independently the appropriateness of the local aerosol climatology selected by MISR for the retrieval(s) (3) providing estimate.s of uncertainty for the retrieved quantities.

Method of Aerosol Optical Depth Retrieval: The total optical depth retrieved using the Langley method [1 I] from sunphotometer observations of the direct solar irradiance in the -400-1000 nrn region consists of components due to aerosols, molecular (Rayleigh) scattering, ozone and water vapor. The molecular scattering optical depth is estimated from measurement of the atmospheric pressure. The difference between the total and Rayleigh scattering optical depths is termed the residual optical depth. Except for the water vapor absorption band itself (-940 nm), continuum or hand absorption elsewhere by water vapor is neglected. The aerosol optical depth in the 940 nm band is obtained by interpolation (extrapolation) between (from) residual optical depth components in adjacent bands. The ozone columnar and aerosol optical depths are retrieved together using a technique developed in [13]. This method avoids the assumption, often employed, of a power law form for the aerosol spectral optical depth variation.

Microphysical Properties of Aerosols, SKYRAD.pack: SKYRAD.pack is a code developed by Nakajima *et al.* [4] for remote estimation 01 columnar equivalent aerosol volume size distribution. single scattering phase function, aerosol optical depth, and single scattering albedo. (This code has kindly been made available to us by Prof. Nakajima). The measured input data required are those supplied by the CIMEL sunphotometer, namely direct solar and diffuse sky radiances as measured in the solar almucantar, and (optionally) spectral optical depth derived from the direct solar irradiance measurement. An iterative scheme is utilized in which the observed radiance distribution in both the almucantar and principal plane is compared to that calculated with a radiative transfer code. For the iteration, initial guesses must be supplied for the aerosol complex refractive index, radius limits on the particle size distribution, the surface spectral al bedo, and initial ratio of sky radiance to direct solar irradiance, obtained from [he observations. When direct and diffuse solar radiation observations are employed together with optical depth measurements, the detectable radius interval for aerosol particle size retrieval is determined to be about 30-10000 nm.

Estimation of surface albedo and complex refractive index: A statistical method developed by King and Herman [6] and King [7] is used to estimate the optimal values of the ground albedo and effective index of absorption of atmospheric particulates. The method compares the ratio of the diffuse to direct transmitted solar irradiance to radiative transfer computations of these quantities and is therefore suited [o analysis of MFRSR observations [5]. The ratio is sensitive to optical depth, particle size distribution and absorption index, and ground al bedo, and is insensitive to other radiative transfer parameters, e.g., the real part of the ret'ractive index, vertical distribution of the atmospheric particulates. Both optical depth and size distribution are inferred from the spectral measurements of the directly transmitted solar irradiance. Comparisons of the observed and calculated ratios allows the inference of effective values of [he absorption coefficient and a weighted average albedo over the entire area which affects the transfer of radiation. An advantage of using the difluse-direct ratio is that absolute calibration of the instrument is not needed.

Inversion of spectral optical depth for size distribution: While size distribution estimates wiii be obtained from the SKYRAD.pack inversions, we wiii in addition employ the inversion technique on spectral variation of aerosol optical depth developed in [14] anti [15] for use with our other direct beam sunphotometers, as well as high resolution spectral optical depth retrievals from the GER spectrometer, which not only potentially increases the number of bins in the size distribution but aiso the retrievable particle size range.

PARABOLA III measurements: Both the upward and downward radiance measurements from PARABOLA III as a function of sun zenith angle are combined together in an algorithm developed by Martonchik [10] to estimate local surface BRF by iterative solution of an integral equation describing reflected light energy at the surface. This procedure explicitly accounts for the presence of directional diffuse light, which cannot ordinarily be accounted for by simple bidirectional measurements with field instruments.

Method of Combining Algorithms for Aerosol Microphysical Property Estimates

The inversion algorithms described provide a significant, sometimes redundant, observational basis for recovery of the required aerosol optical depth and other MISR aerosol climatology parameters. A method of combination of these observations is comprised of the following steps:

(1) The total spectral optical depth will be obtained from direct solar irradiance measurements taken with the Reagan and CIMEL sunphotometers.

(2) The aerosol optical depths as a function of time are then calculated, reconciled, and interpolated to MISR wavelengths.

(3) Simultaneous MFRSR observations of diffuse and direct sky and solar irradiances are interpreted according to the methods of [6], [7], and [8], and estimates of "regional" surface spectral albedo and real and imaginary complex indices produced.

(4) An estimate of the "local" spectral albedo is generated from PARABOLA 111 observations for the currently available range of sun zenith angles. The "regional" anti "local" albedo values are compared, for reasonableness. Both values may be utilized independently in subsequent calculation, but such use of the PARABOLA III measurements compromises them as an independent data set against which radiances subsequently calculated for the aerosol model can be compared.

(s) The measurements of optical depth and estimates of aerosol index and surface albedo (cliffuse/direct-based) are imported to SKYRAD.pack for calculation of size distribution, phase function, and single scattering albedo.

(6) Using the derived aerosol model thus estimated, a radiative transfer code is employed to calculate the downward directed radiance as a function of position over the sky. These radiance values arc compared with PARABOLA III sky radiance observations, which have not yet been employed in the calculation stream, to achieve the current result.

(7) The goodness of fit is judged by comparison of calculated and measured sky radiances. Roughly i 300 such individual PARABOLA III observations will be available for this comparison.

(8) An iterative scheme may need to be established once sensitivity analyses determine the causes of extant departures between calculated and measured quantities.

Closure Experiments and Connections with Direct Aerosol Sampling

Closure experiments arc crucial in deciding on viability of retrieved aerosol and surface reflectance models adopted at experiment sites. For example, radiative closure here implies agreement between irradiance s calculated from a radiative transfer code with a specified aerosol and surface reflectance model, and values measured at the surface. We have exercised portions of the diffuse-direct irradiance procedure described above to study sensitivity of calculated downwelling spectral irradiance to model assumptions about aerosol refractive index and surface (Lambertian) reflectance to force agreement with field measured downwelling irradiance. The observations consistently fell below model-calculated irradiances by 15-20% % for the initial aerosol model adopted. Agreement between model values and observations was easily achieved by increasing the imaginary index of aerosol particles from 0.005 to 0.04, for example, whereas no reasonable adjustment of tile surface Lambertian reflectance proved suitable. The required value of the imaginary index is consistent with the value obtained for midcontinental aerosols of 0.04 from other analyses [16]. The results of such intercomparisons will 10 some extent always remain arbitrary unless the precise aerosol size anti compositional model can be specified by direct observation. Details of these studies will be reported elsewhere.

Sunphotometer and Radiation Networks

Use of the so-called AERONET and 1S1S networks for local validation of MISR aerosol optical depth, particulate microphysical properties and surface irradiance has been mentioned above. Observations of atmospheric optical depth from single instruments refer to line of sight values strictly applicable to tile local area where inhomogeneous atmospheric condi ions prevail. 1 ' 0 assess the spatial variation of aerosol proper-tics anti assess the problems of recovery over larger domains pertinent to the MiSR scale of aerosol retrieval at i 0-20 km, we will employ networks of intercalibrated instruments arranged on regular grids. The use of optimal interpolation anti averaging methods will be used to infer averages at these scales.

FUTURE WORK

During calendar year (CY) 1997 field experiments will be earl-icci out where possible with AirMISR to provide important new data sets for MISR algorithm validation. Choice of field sites represents an attempt to combine together important aerosol anti surface types o! the MISR retrieval strategy. For CY 97 experiments are presently scheduled for the following localities: (i) Jornada Experimental Test Range, NM; Continental aerosols and heterogeneous surface reflectance, late May; (2) Lunar Lake, NV; Arid region aerosols, heterogeneous reflectance, late June; (3) Rocksprings, PA; sLlifate/nitrate aerosols, heterogeneous reflectance; mid August, (4) Monterey Bay, CA; marine aerosol, deep ocean water reflectance, mid-September. In CY 1998, a schedule for aerosol observations thus far includes the following silts: (i) Pacific northwest; biomass burning particulates over forest cover or water, (2) Florida Keys: dust aerosol over marine waters; August-September.

Connections with direct aerosol sampling on the ground, anti by aircraft, as well as determining vertical distributions from such sampling and from lidar observations will be stressed., The use of network observations coordinated with field tests and overflights of AirMISR will also be sought preliminary to application systematically in post launch time.

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